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Unsteady Aerodynamic Modeling of A Maneuvering Aircraft Using Indicial Functions

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Abstract

The generation of reduced-order models for the evaluation of unsteady and nonlinear aerodynamic loads is investigated. This approach is based on Duhamel's superposition integral using indicial response functions. The indicial functions are directly calculated using the results of unsteady Reynolds-averaged Navier-Stokes simulation and a grid-movement tool. Results are reported for an airfoil pitching oscillation and six freedom maneuver of an unmanned combat air vehicle configuration. The accuracy and efficiency of the ROM model are assessed by comparison of the model output with time-accurate computational fluid dynamics simulations. Results demonstrate the ROM method can produce accurate predictions for unsteady aerodynamic loads, along with the advantage that the model predictions require orders of magnitude less time than the time accurate simulation.

Keywords: Reduced Order Model (ROM)， unsteady and nonlinear aerodynamic， indicial response

Introduction

The current combat environment, which rapid changes of flight attitude of aircrafts occur with massive unsteady flows, requires those aircrafts with high maneuverability and agility to further improve their operational effectiveness. The unsteady aerodynamic characteristics can have a significant on the aircraft's stability and control(S&C) characteristics. Thus it is crucial to have an accurate prediction on the complicated unsteady forces for the Stability and Control analysis of an aircraft.

Traditional aerodynamic model is linearized dynamic derivative model, which is under the assumption that the aerodynamic loads are functions of the instantaneous values of flow variables, and depend on this variables linearly[1]. So this kind of model is not quite suitable for the condition that a high performance aircraft is under highly nonlinear and unsteady aerodynamic field. Currently, Computational Fluid Dynamics (CFD) is more and more considered as a powerful tool to simulate unsteady nonlinear flow physics but meanwhile, the full-order model based on Unsteady Reynolds-averaged Navier-Stokes (URANS) equation is too computationally expensive to be used for the S&C analysis during preliminary aircraft design phase. Thus, a new unsteady aerodynamic model is urgently needed to address the imbalance between accuracy and efficiency.

The efforts over the last years have been spent mainly on the development of a reduced order model(ROM) using system identification from experimental and, more recently, from numerical data[2]. The objective of ROMs using CFD is to develop a model that significantly reduces the CFD simulation time required to create a full aerodynamic database, making it possible to accurately model aircraft static and dynamic characteristics from a number of time-accurate CFD simulations.

This paper develops a reduced-order model (ROM) for the unsteady characteristics of manuvering aircrafts by using only a limited number of time accurate CFD simulations and a System Identification (SID) approach,

Duhamel's superposition integral, which is based on the convolution of indicial functions with the derivative of input signals[3]. The indicial functions, which consist of two independent equations named angle and angular rate respectively, are directly calculated by the results of URANS with moving grid technology. For details, the former is realized by translating the grid with a constant velocity vector while the latter one is calculated by simultaneously rotating and translating the grid to keep the angle zero. Even so, the prediction for aerodynamic responses to any arbitrary motion over a wide flight conditions is still time-consuming as a large number of indicial functions need to be computed for each combination of angle of attack and free-stream Mach number. Thus, this paper uses the method of interpolation to fit the relationship between flight conditions and indicial functions[4]. The ROM, along with the interpolating method , can provide a mean for rapid calculation of indicial functions and predictions of aerodynamic forces and moments.

To test the precision and effectiveness of the model generated above, a pitching airfoil and an unmanned combat air vehicle (UCAV) configuration during 6 degree of freedom of maneuver in subsonic speed are considered. The ROM results will be compared with the time accurate CFD simulation.

Body of the Paper

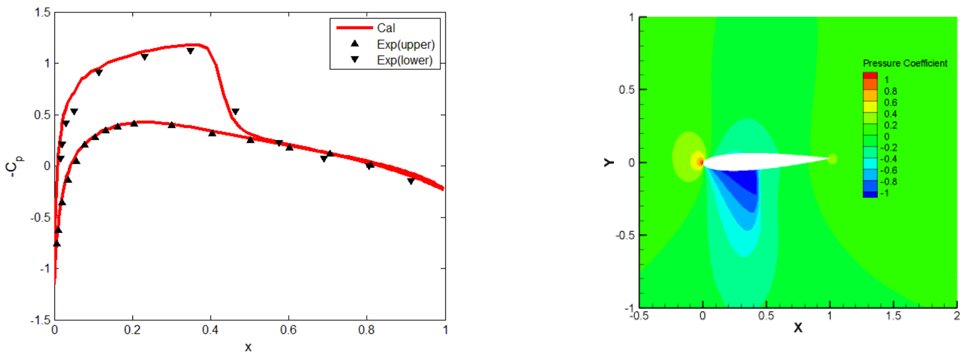
CFD Solver

The flow solver used in this study solves the unsteady, three-dimensional and compressible Navier-Stokes equations. The equations in terms of generalized coordinates are

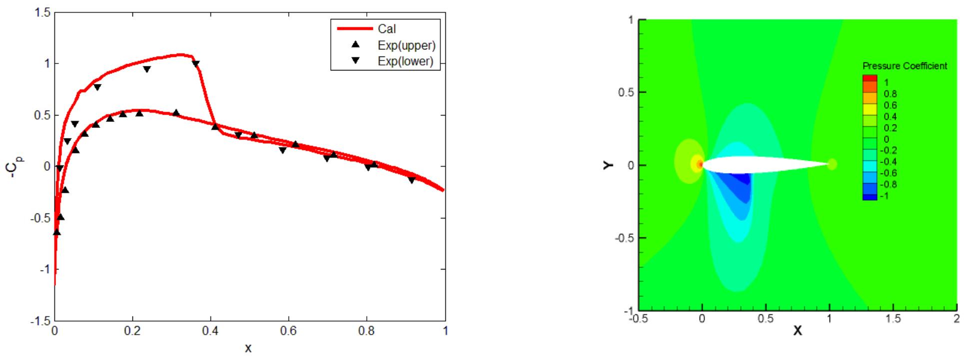
$$\frac{\partial \hat{Q}}{\partial t}+\frac{\partial\left(\hat{F}-\hat{F}_v\right)}{\partial \xi}+\frac{\partial\left(\hat{G}-\hat{G}_v\right)}{\partial \eta}+\frac{\partial\left(\hat{H}-\hat{H}_v\right)}{\partial \zeta}=0 \qquad (1)$$

Where Q is the vector of conserved variables; $\hat{F}$ 、 $\hat{G}$ and $\hat{H}$ are inviscid flux terms; $\hat{F}_v$ 、 $\hat{G}_v$ and $\hat{H}_v$ are viscous flux terms.

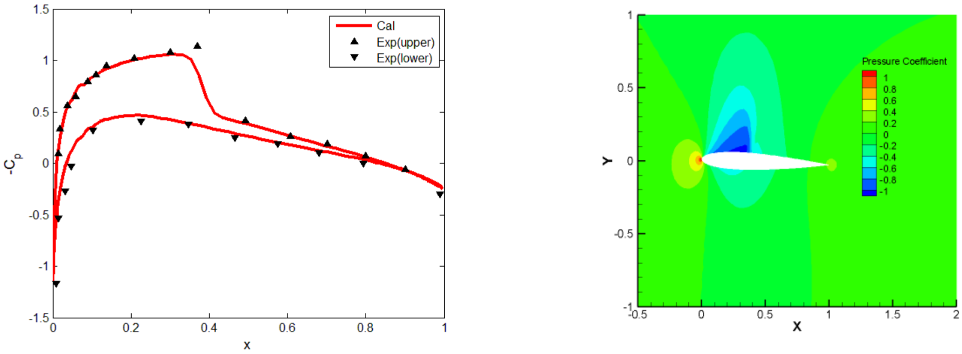
To validate the effectiveness of the CFD solver, the unsteady aerodynamics of the NACA0012 airfoil's pitch oscillation with reduced frequency $k=0.0814$, mean incidence $\alpha_o=0.016^o$ and amplitude $\alpha_m=2.51^o$ are simulated. The results are shown against experimental data in Fig.1, which shows very good agreement in pressure coefficient and CFD simulations can simulate the location of the shock wave accurately. These predictions give confidence in the ability of the current approach to predict unsteady aerodynamics.



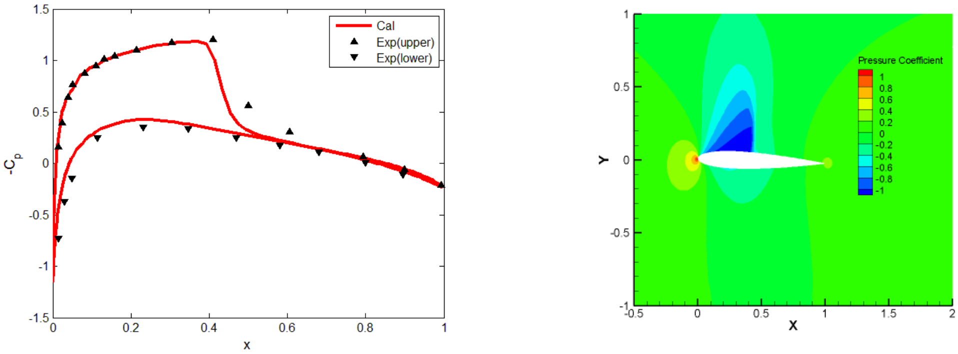
$\alpha=-2.0^o$ *upward*



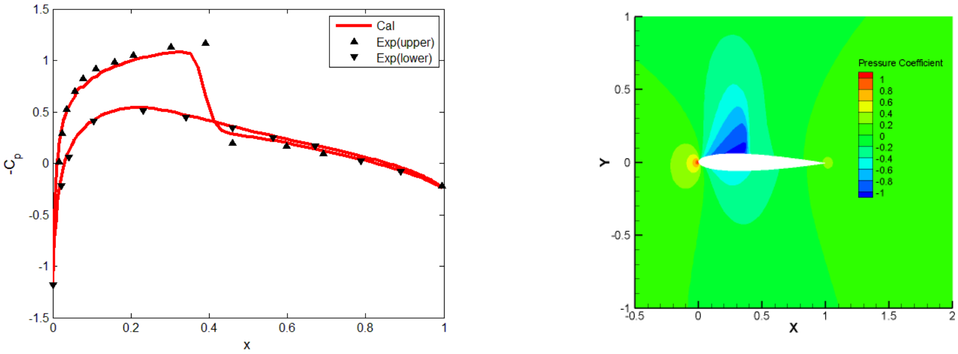
$\alpha = -0.54^o$ *upward*



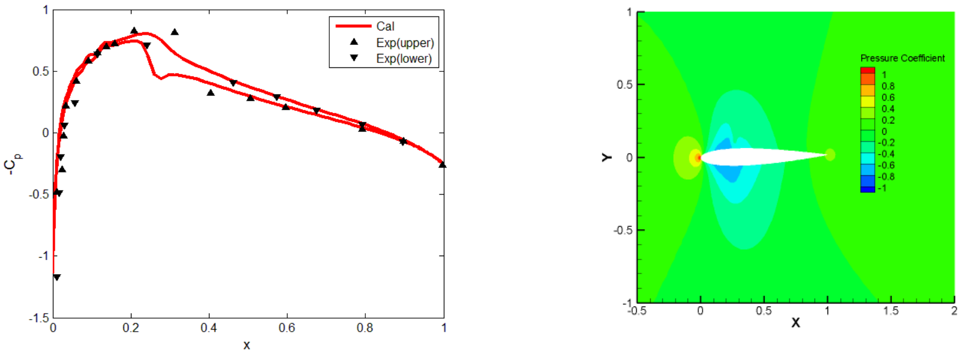
$\alpha = 2.34^o$ *upward*



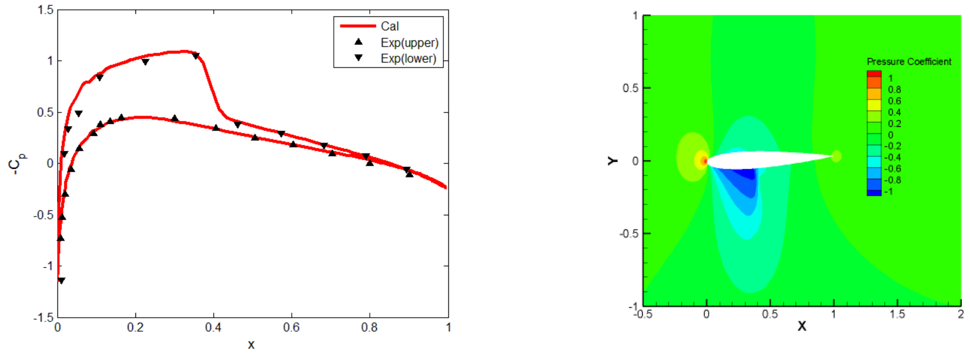
$\alpha = 2.01^o$ *downward*



$\alpha = 0.52^o$ *downward*



$\alpha = -1.25^o$ *downward*



$\alpha = -2.41^{o}$ *downward*

Fig.1 Pressure coefficient and pressure contour for instant angle of attack

Indicial Response Method

The mathematical models of using indicial responses for modeling unsteady aerodynamic load are detailed by Ghoreyshi. In this model ,the response functions are generated at different free-stream Mach numbers. In this paper, a more generated approach is used where the responses in the angle of attack and side-slip depend on both the angle of attack and Mach number. It is assumed that the indicial functions with respect to the angular rates change with changes in free-stream Mach number but not vary with changes in angle of attack for the maneuvers studied. We denote the time response in lift and pitching moment due to step changes in angle of attack, ,and pitch angular velocity q, as $C_{L\alpha}$ 、 C_{Lq} 、 $C_{m\alpha}$ and C_{mq} ,respectively. Ignoring the influence of $\dot{\alpha}$, as it is included in the time history of angle of attack. The unsteady effects in drag force are assumed to be small and therefore are not discusses here. The longitudinal aerodynamic loads at time t are obtained as[4]:

$$C_L(t) = C_{L0} + \frac{d}{dt}\left[\int_0^t C_{L\alpha}(t-\tau,\alpha,M)\alpha(\tau)d\tau\right] + \frac{d}{dt}\left[\int_0^t C_{Lq}(t-\tau,M)q(\tau)d\tau\right] \quad (2)$$

$$C_m(t) = C_{m0} + \frac{d}{dt}\left[\int_0^t C_{m\alpha}(t-\tau,\alpha,M)\alpha(\tau)d\tau\right] + \frac{d}{dt}\left[\int_0^t C_{mq}(t-\tau,M)q(\tau)d\tau\right] \quad (3)$$

Where, C_{L0} and C_{m0} are static lift coefficient and pitch moment coefficient, respectively; $C_{L\alpha}$ 、 C_{Lq}、 $C_{m\alpha}$ and C_{mq} are response functions due to step changes in angle of attack and pitch rate; $\alpha(\tau)$ and $q(\tau)$ are the time history of angle of attack and pitch rate, separately; M denotes the free-stream Mach number.

Assuming that the lateral loads only depend on side-slip angle, roll rate, yaw rate, the unsteady lateral forces and moments using indicial functions are written as:

$$C_Y(t) = C_{Y0} + \frac{d}{dt}\left[\int_0^t C_{Y\beta}(t-\tau,\alpha,M)\beta(\tau)d\tau\right] + \frac{d}{dt}\left[\int_0^t C_{Yp}(t-\tau,M)p(\tau)d\tau\right] + \frac{d}{dt}\left[\int_0^t C_{Yr}(t-\tau,M)r(\tau)d\tau\right] \quad (4)$$

$$C_l(t) = C_{l0} + \frac{d}{dt}\left[\int_0^t C_{l\beta}(t-\tau,\alpha,M)\beta(\tau)d\tau\right] + \frac{d}{dt}\left[\int_0^t C_{lp}(t-\tau,M)p(\tau)d\tau\right] + \frac{d}{dt}\left[\int_0^t C_{lr}(t-\tau,M)r(\tau)d\tau\right] \quad (5)$$

$$C_n(t) = C_{n0} + \frac{d}{dt}\left[\int_0^t C_{n\beta}(t-\tau,\alpha,M)\beta(\tau)d\tau\right] + \frac{d}{dt}\left[\int_0^t C_{np}(t-\tau,M)p(\tau)d\tau\right] + \frac{d}{dt}\left[\int_0^t C_{nr}(t-\tau,M)r(\tau)d\tau\right] \quad (6)$$

Where, C_Y , C_l and C_n denote the side-force, roll and yaw moments, respectively. In the equations above, the response functions are unknown and will be determined in this paper using CFD with a grid movement tool.

CFD calculations of Indicial Functions

The key of using reduced order model to predict the unsteady aerodynamic forces is acquiring exact indicial functions. Lomax[3] and Mazelsky[5] derived approximated functions for two dimensional cases in compressible flow, while, for compressible and three dimensional cases, the only direct method for determination of the unit response functions is the combination of CFD and grid motion technology[3].

As an example for a step change in angle of attack, the grid immediately starts to move at t= 0 to the right and downward, as shown in Fig.2. The translation continues over time with a constant velocity. For a unit step change in pitch rate, the grid moves and rotates simultaneously. The grid starts to rotate with a unit pitch rate at t=0. To hold the angle of attack zero during the rotation, the grid moves left and upward in Fig.3

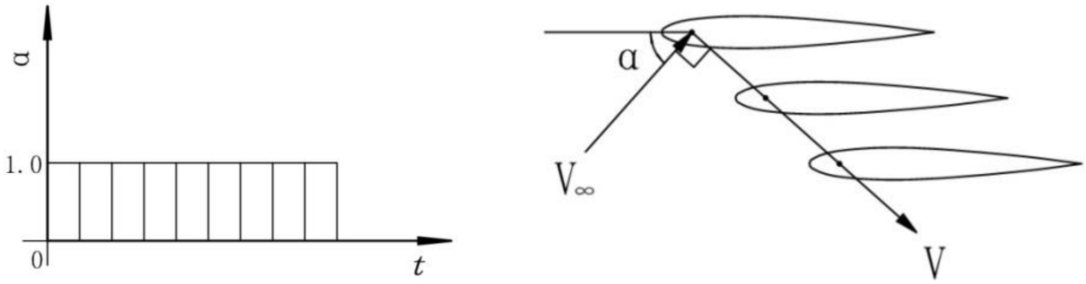


Fig.2 Grid motion for modeling a step change in angle of attack

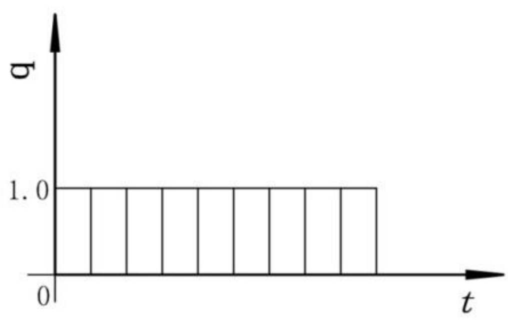


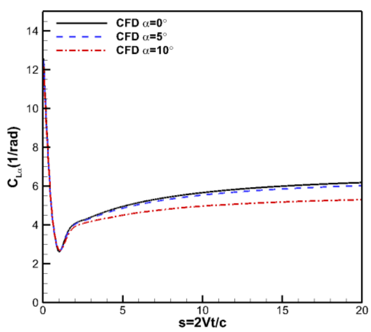
Fig.3 Grid motion for modeling a step change in pitch rate

Test Cases

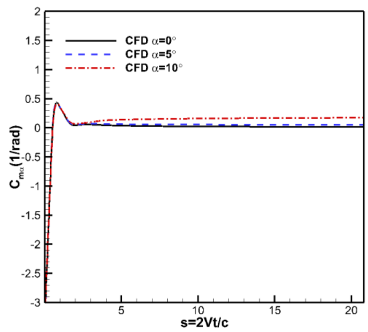
A two-dimensional airfoil and a generic unmanned combat air vehicle(UCAV) stability and control configuration(SACCON) are considered in this paper. The models are evaluated by comparing the predictions with time-accurate CFD solutions.

NACA 0012 airfoil

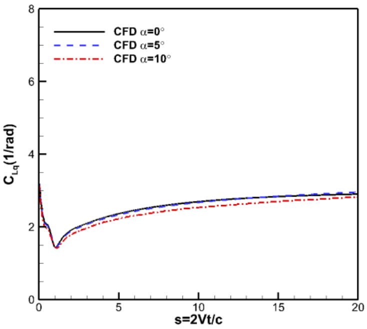
This paper combines CFD with grid motion technology to compute the indicial response. The flow conditions are: Ma=0.3, Re=5.93e6. The indicial response of the airfoil with a unit step change of angle of attack and pitch rate are shown in Fig.4, where the indicial functions per radian are plotted against nondimensional time. The lift has a peak at s=0 followed by a rapidly falling trend. The lift again builds up and asymptotically reaches the steady-state value. While, the pitch moment predicts a negative peak, as the response time progresses, the pitch moment starts to increase and the responses asymptotically reach the steady-state values. Also, the initial values of indicial functions are invariant with angle of attack, but the transient trend and steady-state values change, depending on the angle of attack. Comparing with the indicial response of the pitch rate, the indicial responses of angle of attack are influenced more by the angle of attack.



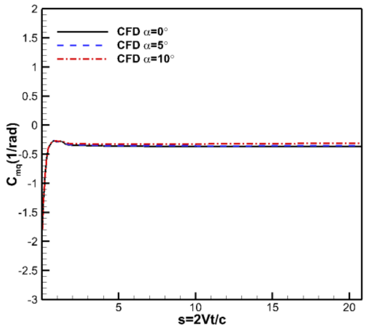
(a) $C_{L\alpha}$ *at different* α



(b) $C_{m\alpha}$ *at different* α



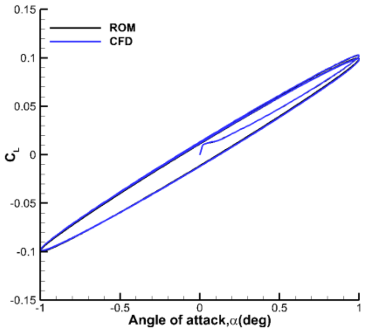
（c） C_{Lq} *at different* α



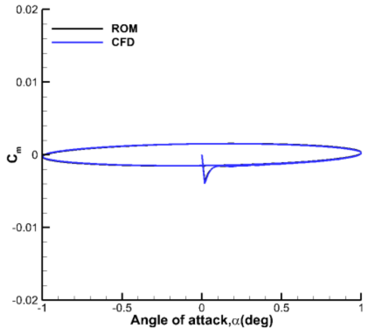
（d） C_{mq} *at different* α

Fig.4 NACA0012 lift and pitching-moment indicial functions

Now a ROM is creased using Eqs.(1) and(2) and are used for prediction in order to check the validity of ROMs, NACA0012 pitch oscillations with frequency of f=2.5Hz are considered. Fig.5-7 show that ROM predictions show very good agreement with time marching solutions. Furthermore, ROM can improve the compute efficiency greatly, in detail, time marching method costs 9620 seconds when simulating 4 periods, while it only takes 10 seconds when a ROM is created.

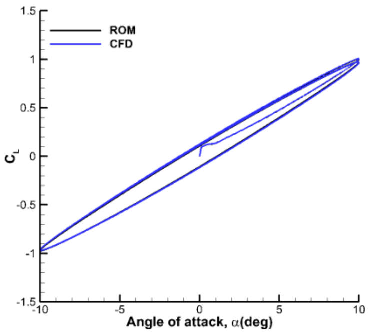


（a） C_L

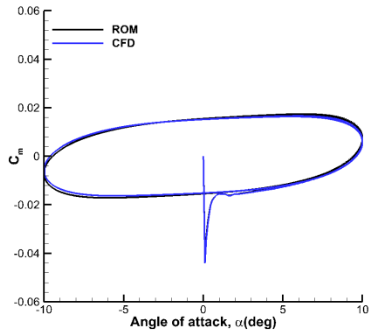


（b） C_m

Fig.5 NACA0012 pitch oscillation with $f = 2.5Hz$ ， $\alpha_0 = 0^o$ ， $\alpha_A = 1^o$

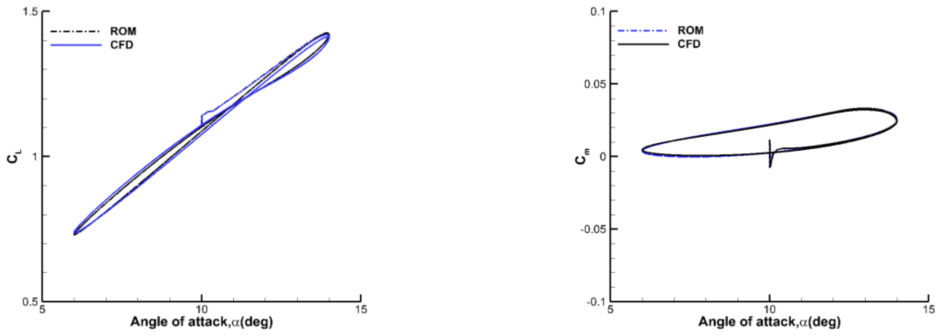


（a） C_L



（b） C_m

Fig.6 NACA0012 pitch oscillation with $f = 2.5Hz$ ， $\alpha_0 = 0^o$ ， $\alpha_A = 10^o$



（a） C_L　　　　（b） C_m

Fig.7 NACA0012 pitch oscillation with $f = 2.5Hz$, $\alpha_0 = 10^o$, $\alpha_A = 4^o$

SACCON UCAV

The SACCON geometry[6] was defined in cooperation between the German Aerospace Center(DLR) and EADS-MAS. The aircraft has a lambda wing planform with a leading edge sweep angle of 53^o, the root chord is approximately 1m, the wing span is1.53m, the reference chord is 0.48m, and the reference area is 0.77m^2.The main sections of the model are fuselage, the wing section, and wing tip. The outer wing section profile is twisted by 5o around the leading edge to reduce the aerodynamic loads and shift the onset of flow separation to higher angles[7].

This kind of UCAV exhibits rather complex vortex-dominated flows, and this configuration exhibit strong pitch up behaviour at a relatively low angle of attack and lateral instability that can lead to serious aerodynamic, stability and control issues.

In this paper, we examine a 6DOF reduced order model based on indicial functions for simulation of SACCON maneuvers. Determination of response functions is a key aspect of such a model, these functions are directed calculated from URANS simulations and a grid motion tool. The current paper also analyses the influence of angle of attack and Mach number on response functions in detail.

Fig.9 shows that angle of attack has influence on the response functions, especially on those of pitch moment coefficient, drag coefficient and roll moment coefficient. It also demonstrates the SACCON model has a characteristic of longitudinal-lateral couple. The initial values of indicial functions are invariant with angle of attack, but the transient trend and steady-state values change, depending on the angle of attack. Fig.10 shows that the initial peak of response functions is smaller for compressible flow. This is due to the propagation of pressure disturbances at speed of sound, compared to the incompressible case, where the disturbances propagate at infinite speed. Thus angle of attack and Mach number should be considered in Eq(1)- Eq(5).

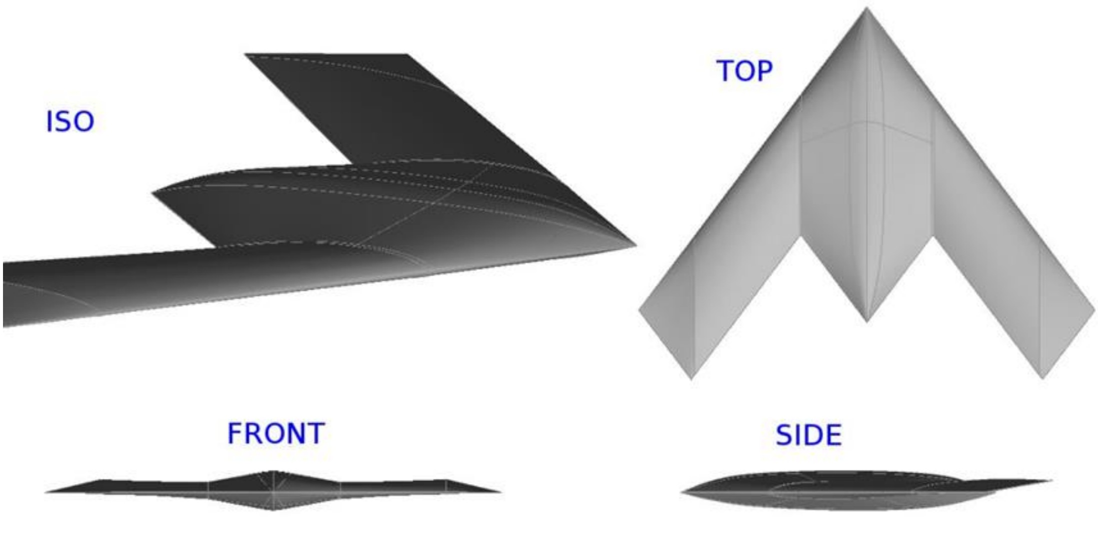


Fig.8 SACCON

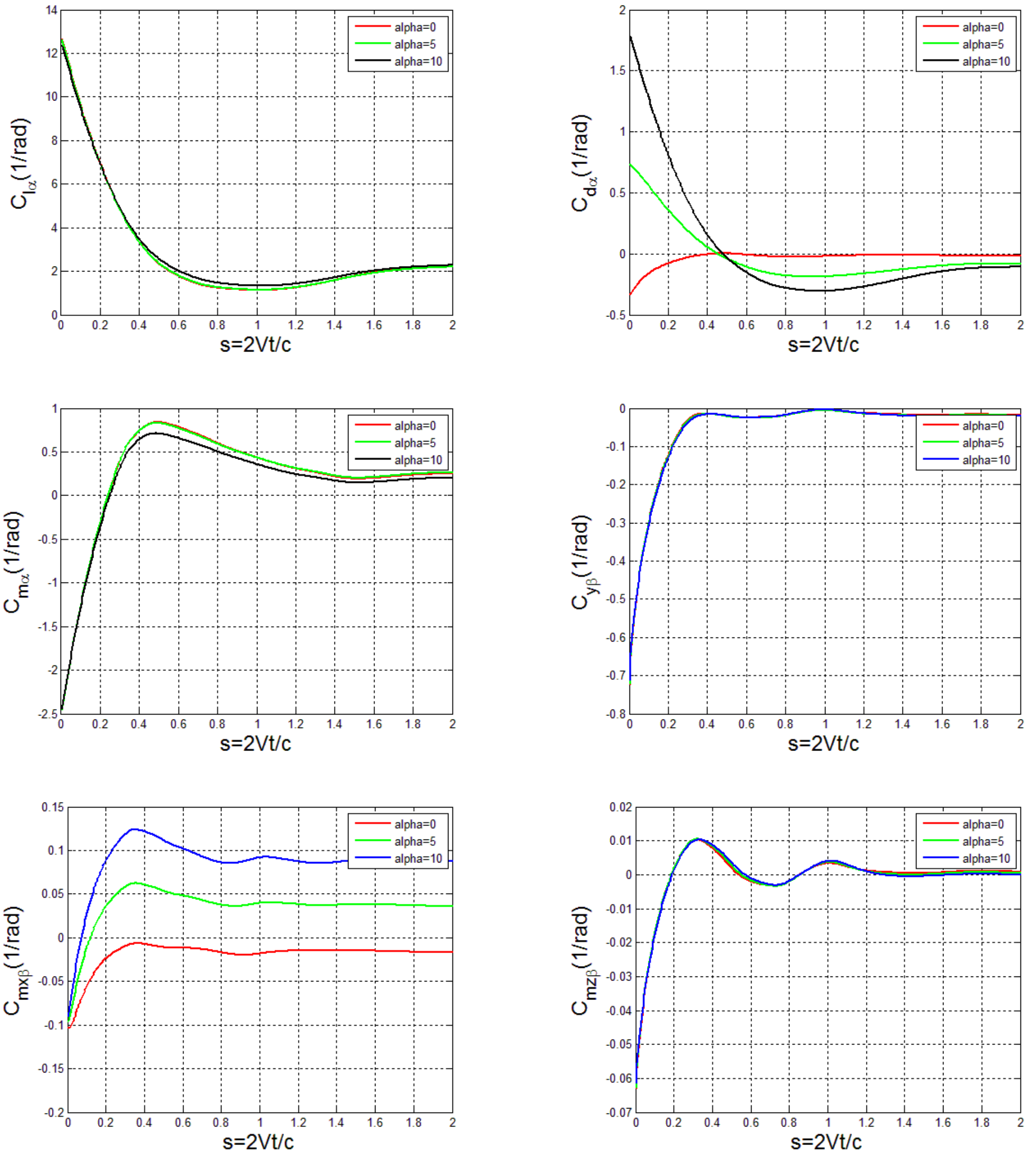
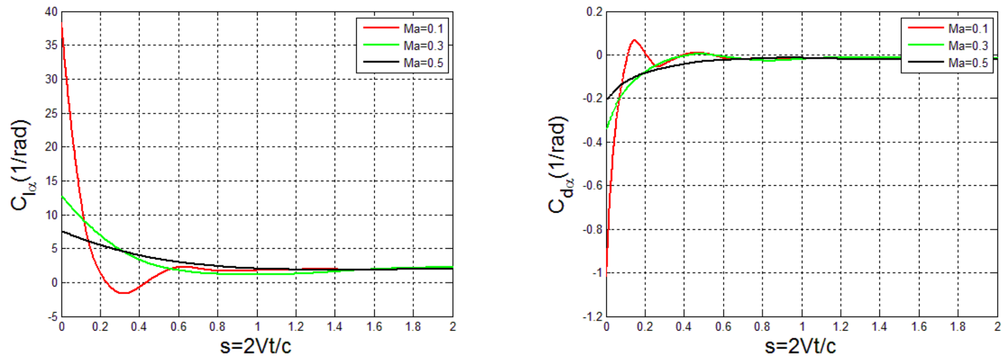
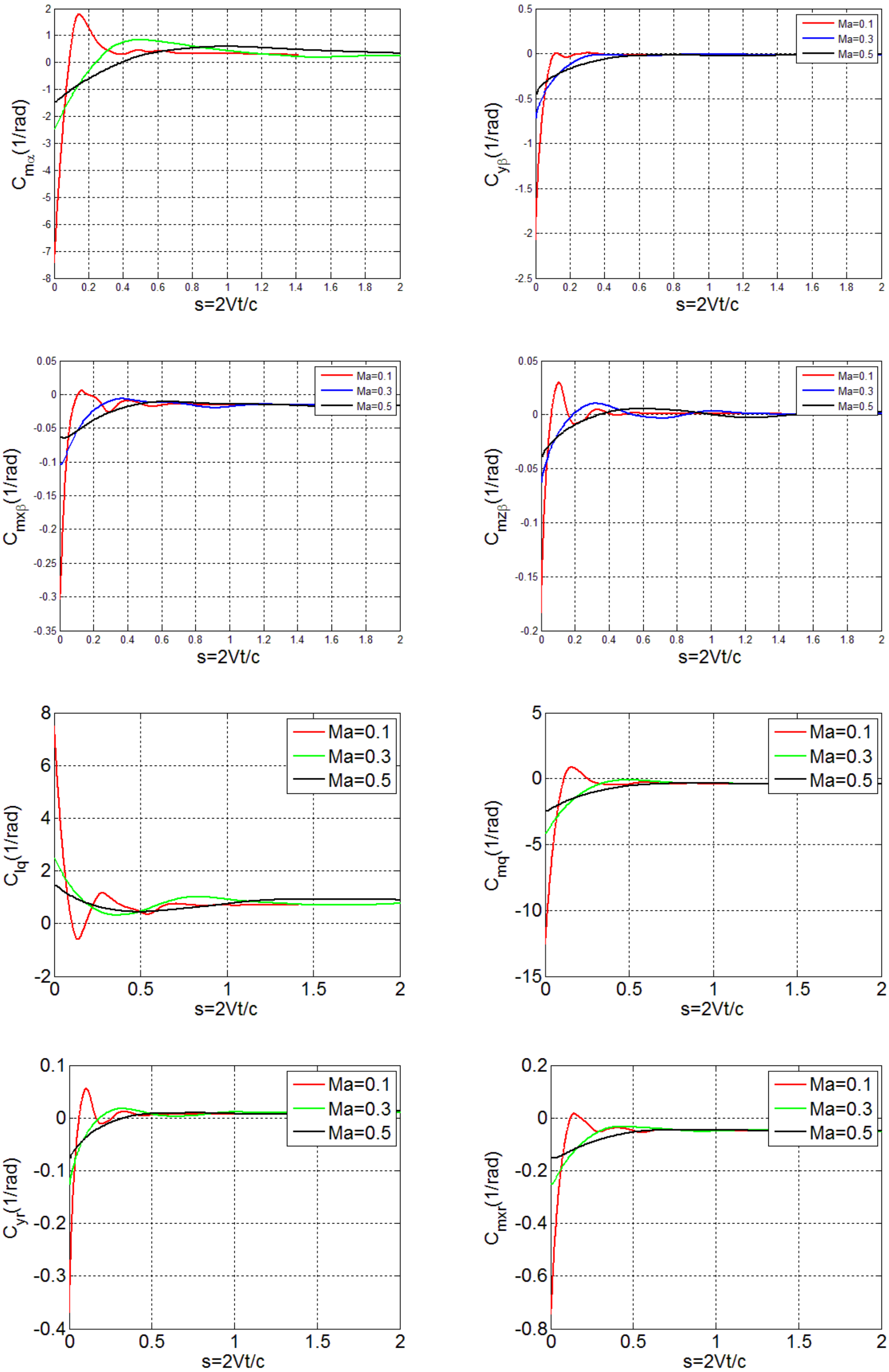


Fig.9 SACCON indicial functions for different α





C_mα(1/rad)
C_yβ(1/rad)
C_mxβ(1/rad)
C_mzβ(1/rad)
C_lq(1/rad)
C_mq(1/rad)
C_yr(1/rad)
C_mxr(1/rad)
s=2Vt/c
Ma=0.1
Ma=0.3
Ma=0.5

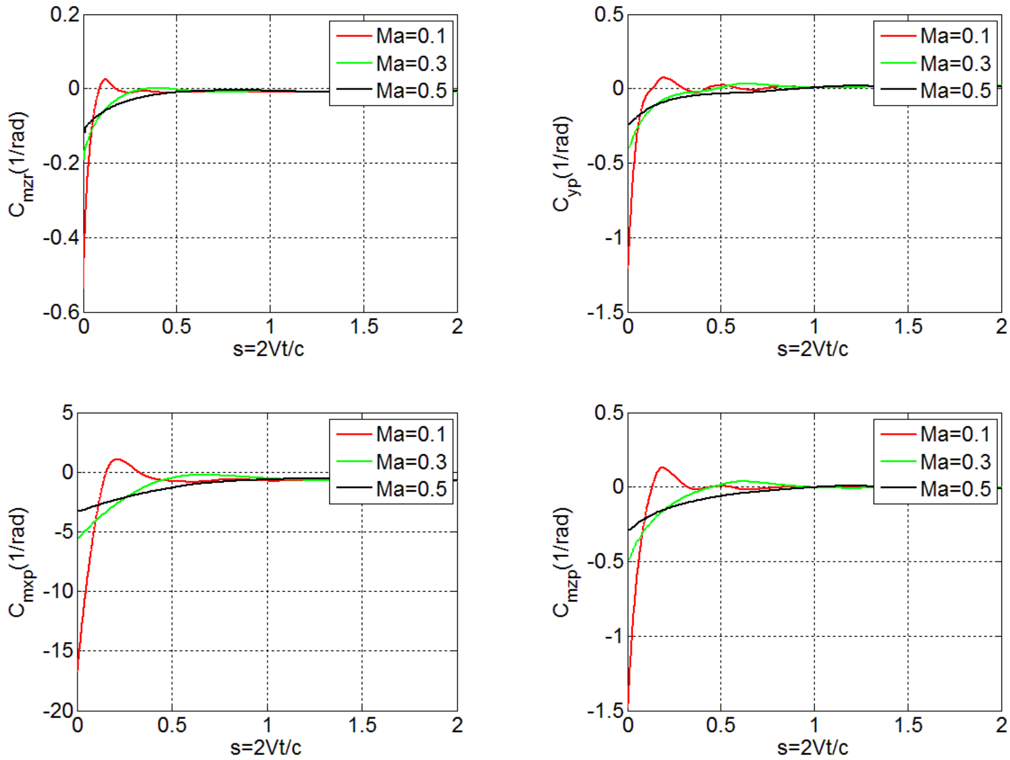
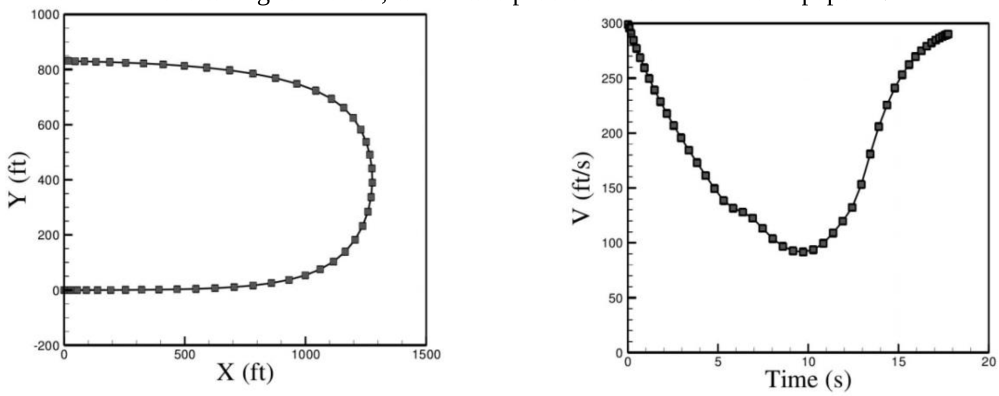


Fig.10 SACCON indicial functions for different Mach number

The ROM equations are used for prediction of SACCON six-freedom maneuver: half Lazy-8[7](Fig.11). The aircraft enters and terminates the maneuver from a straight and level condition. The Lazy-8 maneuver makes a 180o degree turn. The airplane starts a climb steeply to reduce flight speed, the reduced flight speed helps to have a smaller radius turn and total travelled time. Next, the airplane starts to roll as the pitch angle decreases, where at 90o yaw angle, the vehicle is at zero pitch and maximum roll angle. This is followed by a descent trajectory and decreasing of roll angle, increasing pitch angle, and regaining the speed until the vehicle reaches initial velocity and altitude.

Fig.12 depicts the predicted aerodynamic loads of half Lazy-8 maneuver. The comparisons between the created ROM with the time-marching model show good agreements. The time-marching simulations was calculated using RANS simulations with grid motion, which was provided in GHOREYSHI paper[7].



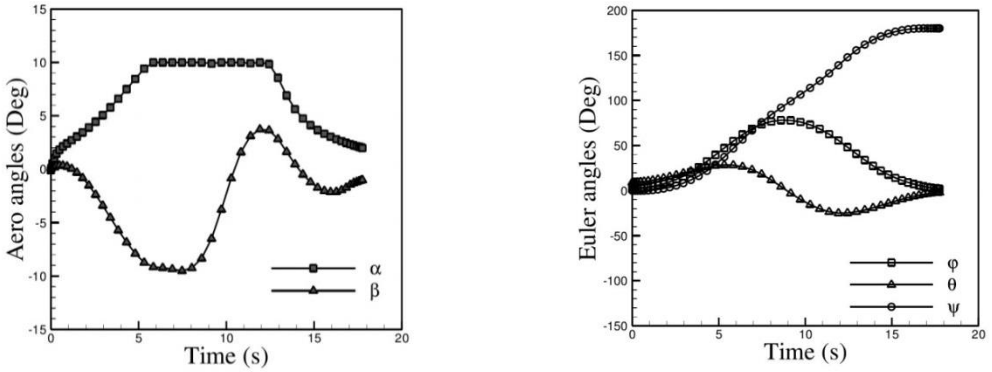


Fig.11 Half Lazy 8

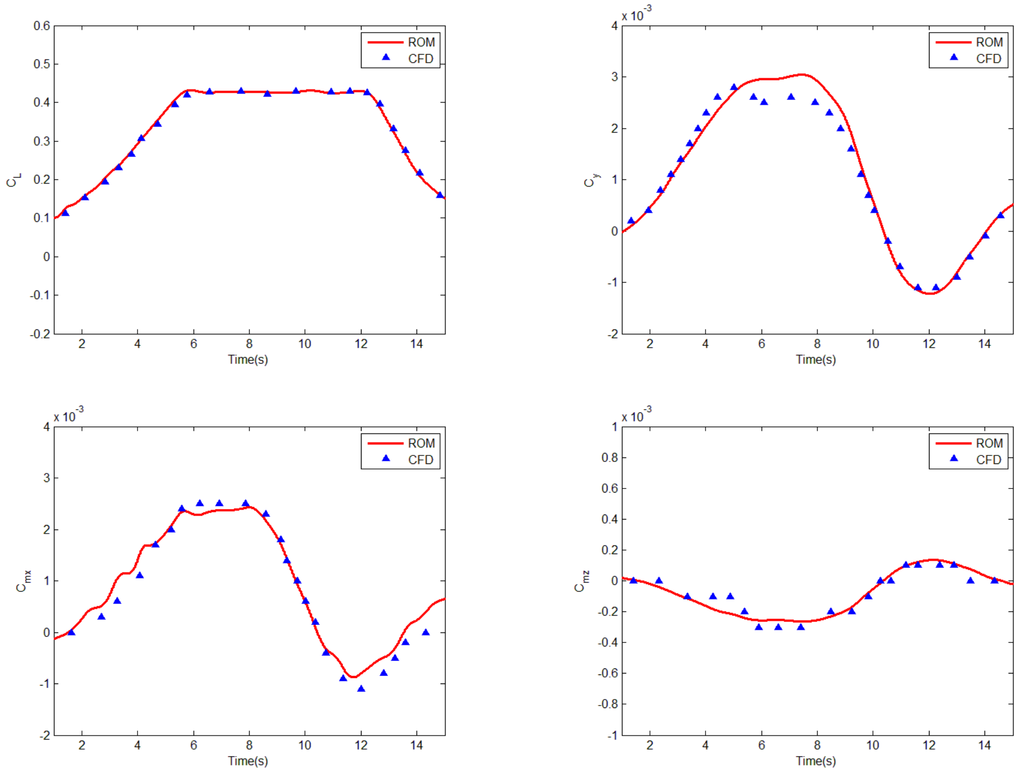


Fig.12 Aerodynamic modeling of Half Lazy-8 maneuver

Conclusions

This paper investigates the use of ROMs that significantly reduce the CFD simulation time required to create a full aerodynamics database, making it possible to accurately model aircraft static and dynamic characteristics from a limited number of time-accurate CFD simulations. The ROM considered was based on Duhamel's superposition integral using indicial (step) response functions. The indicial functions consist of aircraft responses to step changes in the angle of attack, pitch rate, side-slip angle, roll, and yaw rates. All these functions were calculated using direct response simulation in URANS with the aid of rigid grid motion tool.

The test cases used were airfoil pitch oscillation and SACCON six freedom maneuver. The comparison between unsteady simulation of maneuvers with ROM predictions showed the consistency of predictions and the ROM model predictions were generated in a few seconds. The results demonstrate that the ROM methods can balance the efficiency and accuracy, which will be helpful for the analysis of flight dynamic problem.

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